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FRACTURE MECHANICS AND THE FUTURE STRENGTH DESIGN OF MASONRY

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ABSTRACT

The various strengths of masonry are currently determined from tests, with the results being specimen shape and size dependent. The strengths so determined therefore are not the fundamental material properties of the masonry, but some function thereof. Fracture mechanics approaches to the failure of materials and structures account for size and shape effects. The common theme for tensile fracture is the rate at which strain energy in the specimen is reduced with a small increment in crack length - the energy release rate - and how that rate compares with the energy demand rate for crack extension. In compressive stress states, the governing criterion for fracture may shift from energy to cohesive strength. Fracture mechanics and the requirements for application to compressive fracture and masonry are discussed. Preliminary results of a fracture mechanics approach to some modes of masonry fracture are presented.

INTRODUCTION

In working stress or limit states design methods, the strength of masonry is determined on the concept that a stress level can be defined at which the masonry will break. It matters not whether the load effect is compression, flexion or shear; to determine if the masonry is strong enough to resist the applied load effects, the loads are factored up, resulting stresses are calculated and compared against ultimate strengths which have been factored down. The ultimate strengths used in these comparisons are obtained from tests on masonry assemblages or derived from tables based conservatively on the results of tests from previous research.

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It is recognised however that strength tests on masonry prisms or assemblages do not provide an exact measure of the strength of the masonry actually constructed on site. This is not simply because site practice and environmental conditions are typically different to those of the laboratory. There is also the more fundamental issue that the result of a strength test depends on the size and shape of the specimen itself. It is well established for example, that different size prisms give different strengths even when constructed of the same masonry (Maurenbrecher, 1980; Page and Marshall, 1985; Kralj et al., 1994). The load that causes failure of a 2-high prism is higher than that for a 5-high prism, and both are different to the strength of a wall of the same masonry. Flexural tests on a wall give different flexural strengths to those determined from prism tests (Shrive and Tilleman, 1992).

Failure tests on prisms or wallettes do not therefore provide directly the actual material strength, but rather some related value. Empiricism is invoked to utilize the simple ultimate strength (failure load divided by cross-sectional area) of the specimen in estimating the strength that may be expected of a different size and shape of masonry. Masonry is not alone as a material in this phenomenological approach to strength estimation: it has been the general approach for strength estimation of all materials until recently, and remains the approach for many materials. However, in recent decades a new approach to the prediction of fracture has been developing. Originally aimed at predicting the fracture of metal members subject to tensile loads, the methods are beginning to find wider application. The methods all lie under the umbrella term "fracture mechanics".

BASIC CONCEPTS IN FRACTURE MECHANICS

The core premise of all fracture mechanics methodologies is that materials contain flaws, and that cracks which propagate and cause failure of specimens (from microfibres to the Titanic) (Broek, 1986; Gannon, 1995) emanate from these flaws. While flaws would typically be randomly distributed in size and shape in a specimen, for a specimen subject to tension the most critical flaw - the one most likely to cause failure - is a thin crack lying perpendicular to the tensile stress.

Griffith laid the foundation of fracture mechanics methodologies with his pioneering work (Griffith, 1920, 1924). He established that pre-existing flaws in a brittle material subject to tension acted as stress raisers and were the source of the cracks which propagated at specimen failure. By examining the stress at the tip of an elliptical flaw (2D), he showed that the stress concentration at the tip of the flaw easily creates very high local tensile stresses. A sharp crack tip, perpendicular to the applied tension, will magnify the applied stress manifold and thus overcome the interatomic bond strength (cohesive strength).

Griffith argued however that it was not sufficient just to overcome the local cohesive strength. Energy was also required. As the crack propagated, new surfaces were being created, each with surface energy. This energy was supplied by the reduction in strain energy in the specimen as the crack increased in length.

For crack propagation, both criteria need to be met. In tension, the criterion of overcoming the local cohesive strength is easily fulfilled: thus tensile fracture is governed by when the second criterion is met. This latter criterion is that the energy released during a small increment in crack length, through reduced specimen strain energy, is sufficient to overcome the energy required (work done locally to the crack tip and new surface energy) for that small increment in length. That is, the energy release rate must equal or exceed the energy demand rate.

Linear Elastic Fracture Mechanics (LEFM) was the first major quantitative methodology to evolve from Griffith's work. The method requires that the stress field around the crack be essentially linear elastic. The stress field can then be characterized by a stress intensity factor, K, related to the square root of the energy release rate. At some point as the stress is raised, K will reach the fracture toughness of the material, and the crack will then propagate. LEFM has been widely applied to problems involving tensile stress states - complex shapes and loading conditions - and is a reliable predictor of fracture. However, for metals, when the zone of plasticity at the tip of a crack is too large for the assumption of linear elasticity to hold, other methods have to be utilized (J-Integral, CTOD, COD, or R-Curve). All are based in some way on the energy release rate.

The success of fracture mechanics methods in predicting fracture of metal specimens subject to loads generating tensile stresses, has led researchers to assess the applicability of the methods to other materials. Materials as diverse as bone (Pope and Outwater, 1972) and concrete (Mindess and Young, 1981) have been examined, but again in load situations which generate tension within the stress state. Results have been mixed, with much debate in concrete circles for example, as to whether LEFM is applicable. The main use of concrete however is not to resist tensile stresses, but to resist compressive loads: likewise, masonry. However, the application of fracture mechanics principles, both linear and non-linear, to compressive stress states has proven exceptionally difficult. This is because of the differences between tensile and compressive failure.

Whereas tensile fracture is generally typified by a single crack propagating perpendicularly to the direction of maximum tensile stress, compressive failure is generally typified by multiple cracks propagating parallel to the direction of compressive stress (Figure 1). In tension, as the crack increases in length, the cross-section of the unbroken area left to resist the load decreases: the average stress over this area and the stress intensity at the crack tip increase. The energy release rate is maintained and under these circumstances, the crack continues to propagate in what is deemed an unstable fashion. In contrast, in compression, as the cracks increase in length, the cross-sectional area to resist the load remains essentially the same. The average stress appears not to change. Close to final failure, the cracks coalesce to form macro cracks which in turn create columns of material in the specimen. These columns spall off or buckle away from adjacent more highly confined or more lightly stressed zones, and the specimen fails. In more brittle materials and structures the cracks perform their destructive task rapidly, but compressive failure frequently involves the stable growth of cracks parallel to the direction of compression.

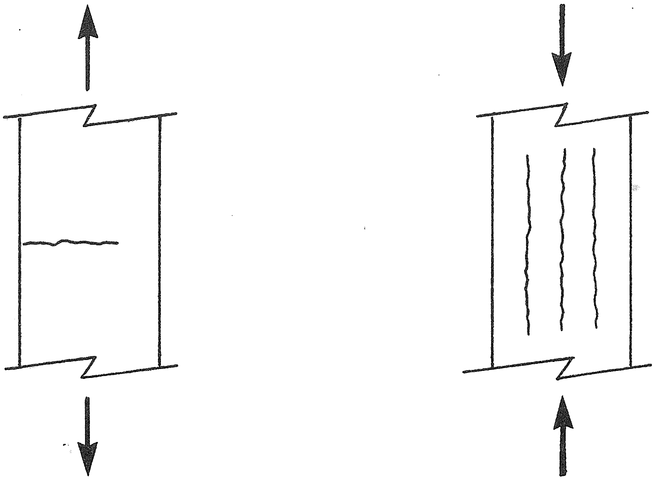

Figure 1. Uniaxial tension in a material typically leads to failure from a single crack perpendicular to the tension. Compressive failure on the other hand is typified by multiple cracks parallel to the compressive stress.

COMPRESSIVE FAILURE

In addition to the more obvious macroscopic differences between tensile and compressive failure, there are two fundamental issues which make the analysis of compressive failure more difficult. Firstly, in analyses of tensile fracture, cracks are modelled as being infinitely thin. In series expansion of analytic expressions, only the first term need therefore be considered. Crack length is the important parameter, and crack width typically has no impact on the solution. However, in a uniaxial compressive stress field, an infinitely thin crack parallel to the direction of compression does not alter the stress field one iota. As the infinitely thin crack increases in length, the stress field remains unaltered and consequently there is no reduction in strain energy in the material (El Rahman and Shrive, 1986). The energy release rate is automatically zero. Hence the most commonly used assumption for analysing tensile failure is simply not applicable to compression failure.

Secondly, the asymmetry of the bond force/interatomic spacing relationship must be recognized. In order for a crack to propagate, interatomic bonds must be broken. The relationship between bond force and interatomic spacing (Figure 2) reveals quite clearly that only tension can break a bond. Hence for a crack to propagate in a compressive stress field, tension must somehow be generated. This is completely different to the tension fracture situation, where there is no necessity to generate compression.

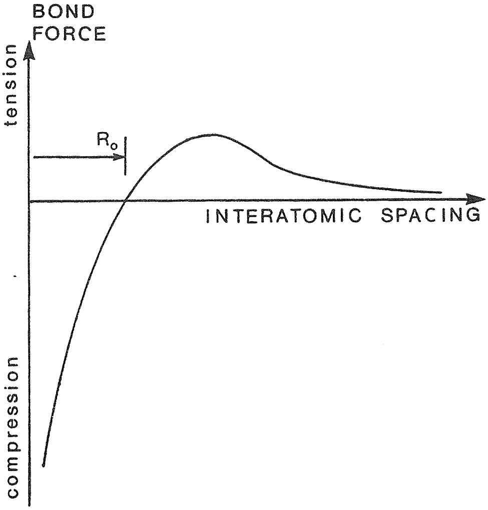

Figure 2. The bond force/interatomic spacing relationship shows that compression can never break a bond, only tension. R_o is the equilibrium spacing.

Given that many different materials, masonry included, fail with similar cracking patterns in similar uniaxial (Peng and Podnieks, 1972; Shrive and El Rahman, 1985) and biaxial compressive (Page, 1982; Vile, 1968) stress states, a similar cause of cracking must exist. Tensile stresses are generated around flaws of finite width in compressive stress fields (Figure 3). Indeed, lintels are placed over openings such as windows and doors in buildings to resist these tensile stresses. Flaws are found in all materials including masonry (Shrive, 1983; Xiao and Jiang, 1994) and it is unlikely that there is a sudden change in the cause of fracture as one moves from tension, through tension-compression to compression in stress space. The presence of flaws causing crack propagation throughout stress space is thus a logical extension of tensile fracture mechanics. Indeed, in concrete technology, the removal of large flaws produces very high strength concretes (Birchall et al., 1981), whereas the introduction of 3-4% air voids in air entrainment reduces strength by 20-30% (Neville, 1981).

Using a 3-D ellipsoidal void in an infinite medium as a model of a flaw in a material, cracking patterns as observed experimentally have been predicted. Energy release rates have also recently been calculated which account for the effect of flaw size (Wang and Shrive, 1994). A shift in the dominant criterion from energy to cohesive strength has been predicted as the stress state becomes more compressive. Indeed, in pure triaxial compression, no tensile stresses are generated at the tip of any flaw, so although plenty of energy may be present, cracking should not be expected. Materials such as rock

(Bridgeman, 1952) and concrete (Hobbs, 1971) have been shown to flow plastically under high hydrostatic compression, rather than fracture.

Again recently, the spheroidal void has been shown to be the most critical shape for initiating crack propagation in compression (Wang, 1994). Simple equations are available for the stresses at apexes of such a void (Goodier, 1933), but an analytic expression for energy release rate has not been derived. The current solution requires numerical integration and the evaluation of elliptic integrals. With elementary estimates of accumulating damage, the model can however, predict correctly the sort of cracking which occurs in concrete and masonry specimens in compression tests (Wang and Shrive, 1993). Xiao and Jiang (1994) have also considered the use of damage mechanics. Such approaches however, are unlikely to yield simple expressions for deriving the critical energy demand rate for compressive fracture and the ability to utilize that demand rate to predict the "strength" of differently sized and shaped specimens.

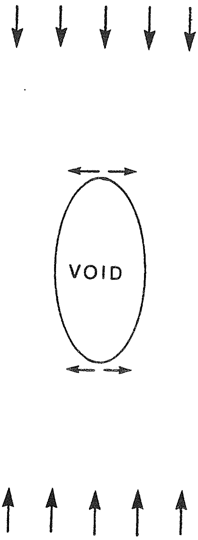

Figure 3. As compressive stress flows around a void of finite width, tension is generated at the tip of the void, and would cause a crack to propagate parallel to the compression.

COMPRESSIVE FRACTURE REQUIREMENTS

Progression to using fracture mechanics for predicting compressive fracture therefore requires a number of advances in analytic capability. A crack changes shape as it propagates from an initially spheroidally shaped void. The energy release rate will vary with the shape and width of this growing crack. A method for determining the maximum energy release rate curve therefore needs to be established for different materials, different initial void sizes, and differing multiaxial compressive stress states. This method will need to account for the potential change in dominance of the criterion governing crack propagation from the energy criterion to the cohesive strength criterion. The method will also need to account for the fact that in some stress states no propagation will occur at all. A method also needs to be established for determining the minimum number of major cracks required to cause failure of specimens of different shapes. These two methods need to be combined, with a flaw size distribution, to predict the minimum strength which can be expected of a specimen, given the fracture toughness or energy demand rate. These latter should be material constants for materials and specimens to which LEFM applies.

It is unlikely that the methods foreseen above will be constituted simply by analytic means. However the results of numerical calculations will have to be expressed as relatively simple equations (e.g. the energy release rate curves) for inclusion in design codes. Design methodologies based on strength predictions founded in fracture mechanics are likely to be more reliable and thus less conservative than current methods.

CURRENT POSSIBILITIES WITH FRACTURE MECHANICS

While considerable progress needs to be made on the analytic front, modelling of failure modes of masonry using fracture mechanics concepts can be performed numerically with appropriate software. A general purpose finite element program for analysing fracture is FRANC (FRacture ANalysis Code) (Wawrzynek and Ingraffea, 1993). FRANC has been used to model fracture in concrete (Linsbauer et al., 1989), and predicts cracking on the basis of LEFM. Cracks have to be "seeded" in the model. That is, one has to assume (guess) where a crack might start and place a flaw in the model at that site. In the program, the stress intensity at the tip of the flaw is determined, and checked against the specified fracture toughness of the material. When the stress intensity exceeds the fracture toughness, the crack extends by an amount controllable by the user. The model is remeshed near the crack tip and then reanalysed to check whether, and in which direction, the stress intensity still exceeds the fracture toughness. Once the crack starts propagating therefore, the program determines the direction of propagation. For masonry, that direction could be along a weak interface such as a bed joint. The performance of the software in dealing with interfaces had to be improved (see later). The program allows multiple cracks to propagate as long as they do not come too close to one another, a structural boundary, or an interface. These features also needed improvement for the program to be useful in the analysis of masonry.

The approach in FRANC is therefore different to that adopted by Ali and Page (1987). In their finite element model, these authors used three different failure criteria to establish cracking or crushing of solid brick masonry subject to concentrated loads. Failure occurred in a whole element (smeared crack model), with the modulus matrix of that element being modified to account for its mode of failure. The model was reanalysed to redistribute the load that element could no longer bear. Cracks were modelled as growing as successive elements failed. This method restricts the direction of crack propagation to the directions of the mesh defined. A similar restriction exists for the discrete crack model of the same authors (Ali and Page, 1986) where cracking is modelled as separation of nodes in the mesh. Some knowledge of how the masonry is likely to fail is therefore required beforehand so that the mesh can be established which will allow the appropriate directions of crack propagation.

In contrast, our intent has been to develop a technique whereby a numerical model of a masonry specimen can be loaded (in the computer) and the cracking behaviour predicted correctly without a priori knowledge of that behaviour. How many cracks will propagate, from where will they start and whence will they go?

These questions arise from the results of concentrated load tests on hollow concrete masonry wallettes. The wallettes were seven courses high by four units wide. The top course was a reinforced bond beam. When concentrated loads were applied to the centre of the bond beam, the failure was typical of that observed for hollow face-shell bedded masonry: the wallettes failed by splitting in their own plane. However when the concentrated load was applied at the end of the wallettes, the failure mode was entirely different. The bond beam lifted off the underlying masonry at the end distant from the load, and the masonry beneath the load spalled off (Figure 4). This mode of failure is more like that of solid masonry. What would failure look like and at what load would failure occur if the design detail were different - for example,no bond beam and no grouting of cores; grouting of cores local to the bearing plate in one, two courses? Of the numerous possibilities, which design detail is best? A fracture model is needed where numerous initial potential crack start points can be "seeded", and the propagation of cracks followed. The model can subsequently be verified by experimental test on specimens with the most promising strengths based on the numerical results.

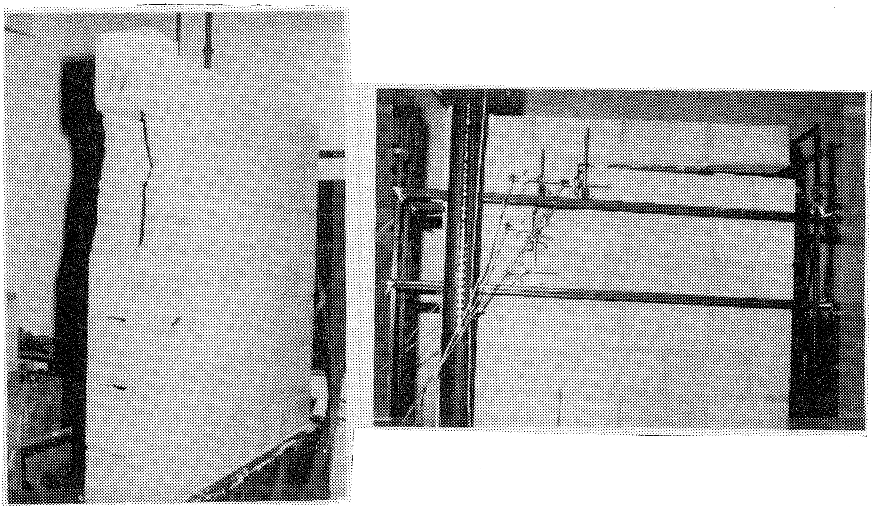

Figure 4. Failure of a face-shell bedded masonry wallette with a load on the end. The bond-beam rises as the end spalls off.

The program, FRANC, is therefore being adapted to the anisotropy of masonry. Cracks may propagate along head and bed joints, or through masonry units. Different fracture toughnesses will resist propagation in the different modes. The following features therefore need to be included in the software.

1. Cracks may propagate along a weak line (on bed or head joint) even though this may not be perpendicular to the greatest tensile stress in the model.
2. Cracks may turn along interfaces at 90° as they propagate through head and bed joints, or may propagate along an interface, through a unit and back onto a different interface.
3. Crack propagation needs to be automated.
4. Cracks may have to propagate to a boundary (structural or another crack) before specimen failure occurs.
5. Cracks may coalesce.
6. Cracks will propagate in compressive stress fields.

The first five features have been addressed to date, with reasonable results. For example in Figure 5, the wallette test is modelled, with a point load at the left-hand end.

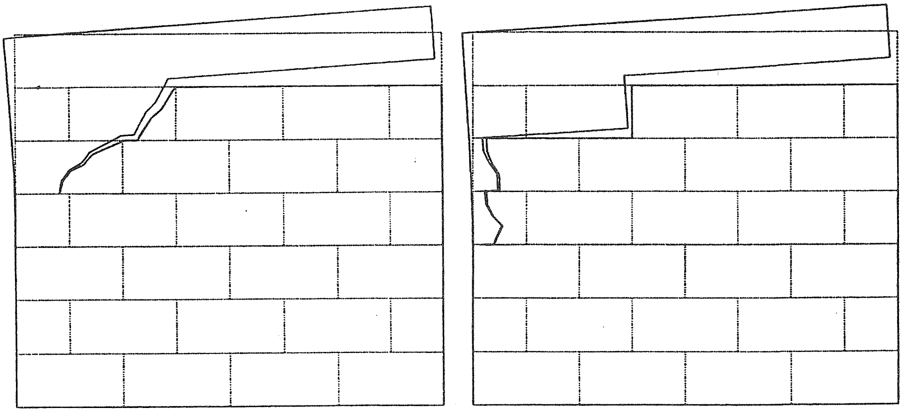

Figure 5. A crack seeded in the bed joint beneath the bond beam propagates to give similar cracking patterns to that observed experimentally.

The concentrated load is applied on the left-hand end of the wallette. This eccentric load creates tension on the right hand edge. A crack seeded on the right hand edge propagates along the interface between the bond beam and the underlying masonry until it is halted by the compression caused by the dispersion of the concentrated load. The crack then progresses down and towards the edge of the specimen to cause failure. The model still needs to be calibrated with experiment for ultimate load prediction. Also, the model is 2D, and thus cannot incorporate the more usual mode of failure of face-shell bedded masonry. In order therefore to obtain estimates of ultimate load under concentrated loading at or near the end of a face-shell bedded wall, both this model and that of Sayed-Ahmed and Shrive (1995) will need to be used. The lower predicted ultimate load should indicate which mode of failure will occur.

The fracture model currently under development has wider potential applicability than just concentrated loading. Two of the three cracking modes observed by Mann and Müller (1982), under shear and compression loading have already been modelled. Another case already within the model's capability is cracking along the bed joints only which has been observed in some stress states (Page 1982, Ganz and Thürlimann, 1982). The ability to model multiple cracking in compression will be a critical component of providing the capability to model masonry fracture in general 2D load cases.

CONCLUSION

Fracture mechanics methods have been developed as successful predictors of the tensile failure of metal specimens; better predictors in many cases than the more established "strength" approach. The methodologies are being adapted for use with other materials. The analytic difficulties with compressive fracture indicate that the development of equivalent approaches for compressive stress states will take time. Meanwhile the application of fracture mechanics principles to other loading situations in masonry which involve tension within the structure is feasible. A number of the cracking patterns observed experimentally can be modelled. The method holds significant promise for improved prediction of the strength of masonry specimens.

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